Corrosion Modeling, Simulations and Assessment through Intelligent Computations

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Outline of the talk …..

- Background
- Objectives
- Modeling, Simulation & Assessment
- Summary & Future Work

Corrosion

- A growing problem in aging aircraft
  - Military (Army, Air Force, Navy)
  - General Aviation
  - Commercial
  - Others

Impact

- 200 billion dollars per year in the aircraft industry alone…

✓Extend Design life

✓Improve Detection/Inspection Methods

✓Monitoring and Prediction Methods

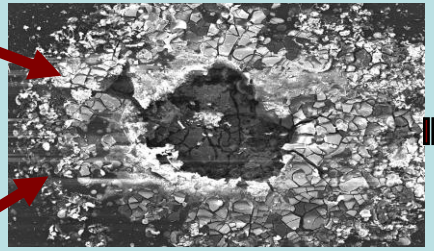
Impact of Corrosion

- Corrosion leads to part failure…

Structural Integrity Assessment

Structure

Material



Corrosion Damage

Structural Integrity ?

Significance Maintenance

Advanced Computer Vision and Computational Intelligence methods integrated with remote operations using distributed maintenance and inspection networks

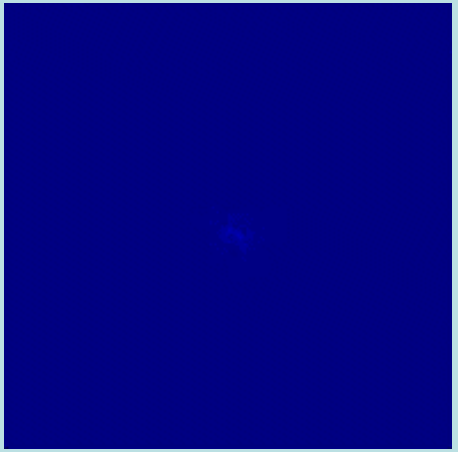
(Data base of corrosion damage from different material/structural systems, which can be shared via internet for repair and failure histories)

Technologies of Interest - Better coatings, reliable inspection methods, modeling and predictions methods

Current Work

- Many people are working with corrosion models – empirical, experiments, continuum, discrete, mechanistic, stochastic, and others ….

  – Anti-corrosive coatings
  – Material redesign
  – Better Inspection Methods



But…

Our approach is based on computational simulations.

- **Mapping the corrosion damage in terms of quantitative measurements, which can be used for further growth/failure analysis on structural integrity and life prediction**

Intelligent Corrosion Damage Assessment System (ICDAS)

- A multidisciplinary approach
  - Image Processing
  - Computer Vision
  - Material Mechanics
  - Artificial Intelligence
  - Structural Analysis/Methods
  - Mathematics

Objectives

- **Goal: Estimate the severity of the corrosion damage - structural integrity and life prediction**
- Modeling and simulation of corrosion pit damage process (Part I)
- Assessment of corrosion damage (Part II)

- Provide a “Safety Index” to assess the long-term durability of aging structures/materials
- Integrate the corrosion damage quantification with user friendly environment and GUI

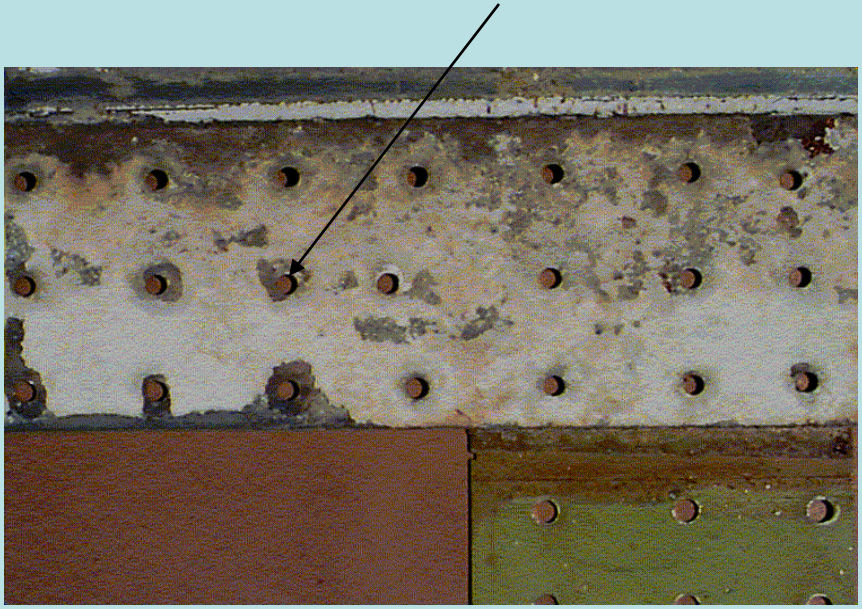
Corrosion Pit Initiation and Growth Model (Part I)

Modeling Surface Corrosion in Materials

Approach

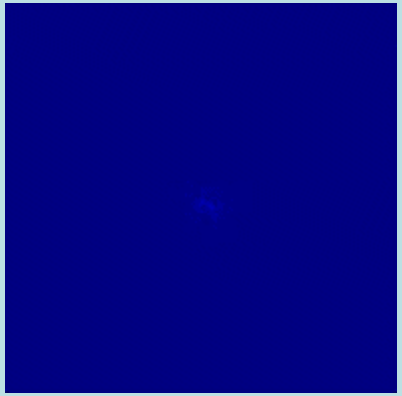
- A discrete dynamical computational model based on cellular automata (CA) is being developed to simulate the pitting corrosion process.
- The model is at the micro-level based on chemical parameters.
- The model is general and can apply to different materials.

Severe corrosion at the Lap Joints and rivet holes



Spatial Simulation

2D Simulation

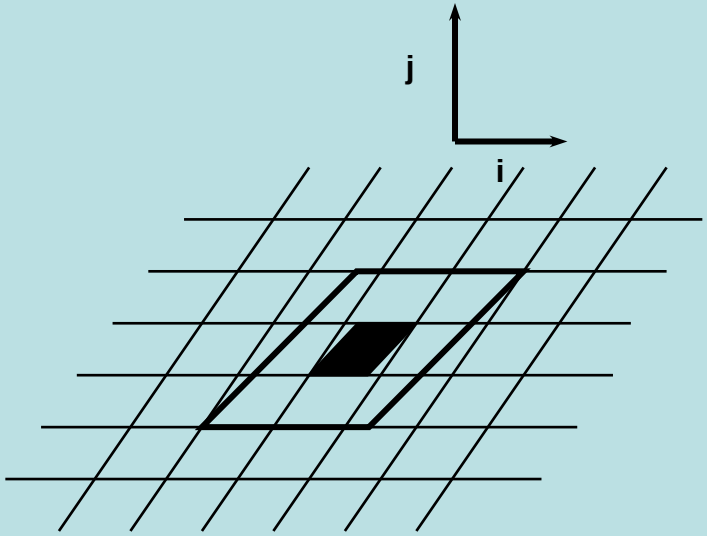


Single Pit

Multi Pit

Corrosion Growth Model using Cellular Automata

- The material surface is divided into grid of small uniform squares, or cells.
- The local cellular automata rule is enforced on a neighborhood window of cells.
- The corrosion growth at the center cell is defined by the state of all the cells in this neighborhood through the local rule.



Governing Equation

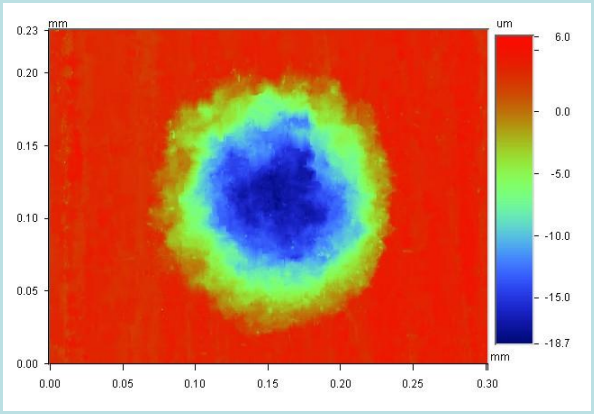
$$S(t+1,x) = S(t,x) + k_1 f(S(t,x)) + k_2 R_1(f(S(t,x+c_1)), f(S(t,x+c_2)),$$
$$f(S(t,x+c_3)), f(S(t,x+c_4))) + k_3 R_2(f(S(t,x+d_1)), f(S(t,x+d_2)),$$
$$f(S(t,x+d_3)), f(S(t,x+d_4))) + k_4 \Delta$$

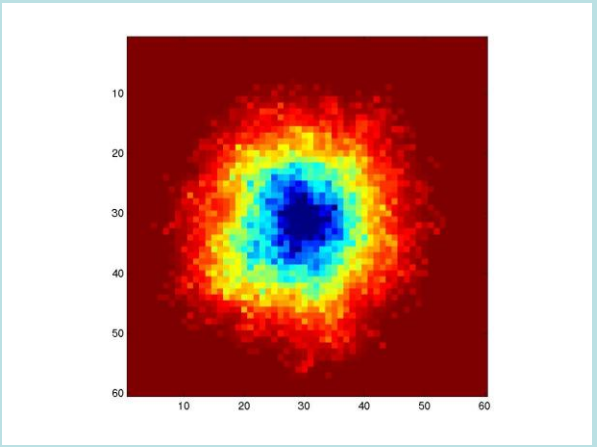
Chemical Parameters

$$k_1 = \lambda * (PH - 7)^2 * step(4,8.5) * e^{Pot} * \frac{1}{T} * C * D * z$$

- λ is a discount factor;
- PH is the ph value of the solution;
- step(4,8.5) is a function with value 0 between 4 and 8.5, and 1 otherwise;
- Pot is the potential difference between the metal and solution;
- T is the absolute temperature;
- C is the concentration of the reaction species;
- D is the diffusivity of the reaction species;
- z is the charge of the reaction species.

Simulation Results





(a) Experiment (b) Simulation

Comparison of simulated data with the experimental data from Dayton, the time is 3600 seconds and the potential value is set at 0.57v (blue indicates corrosion)

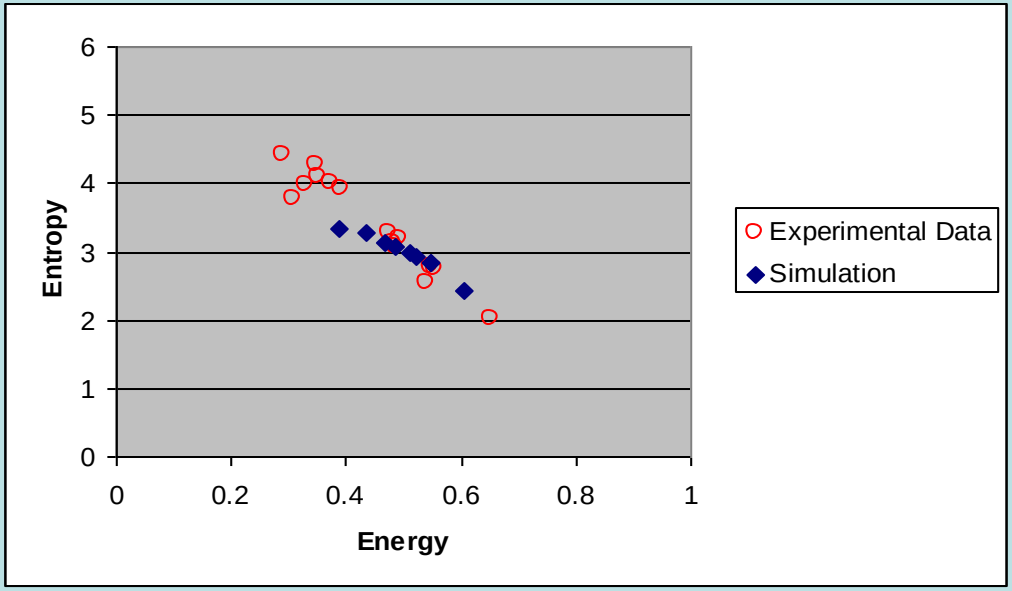
Validation Process

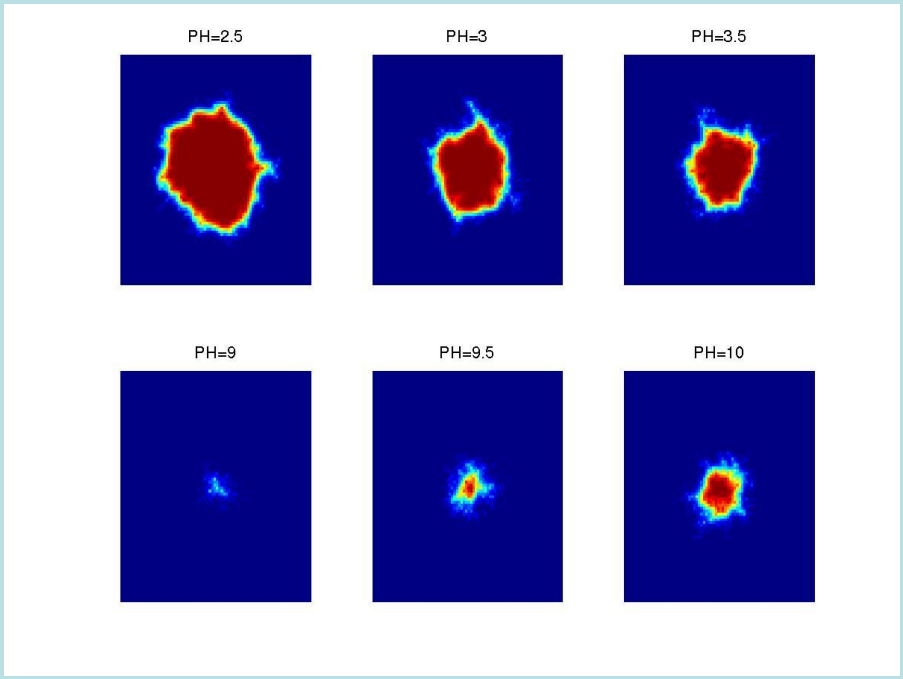
Experimental Data - Image

Simulated Image

Features Extraction through Image Processing

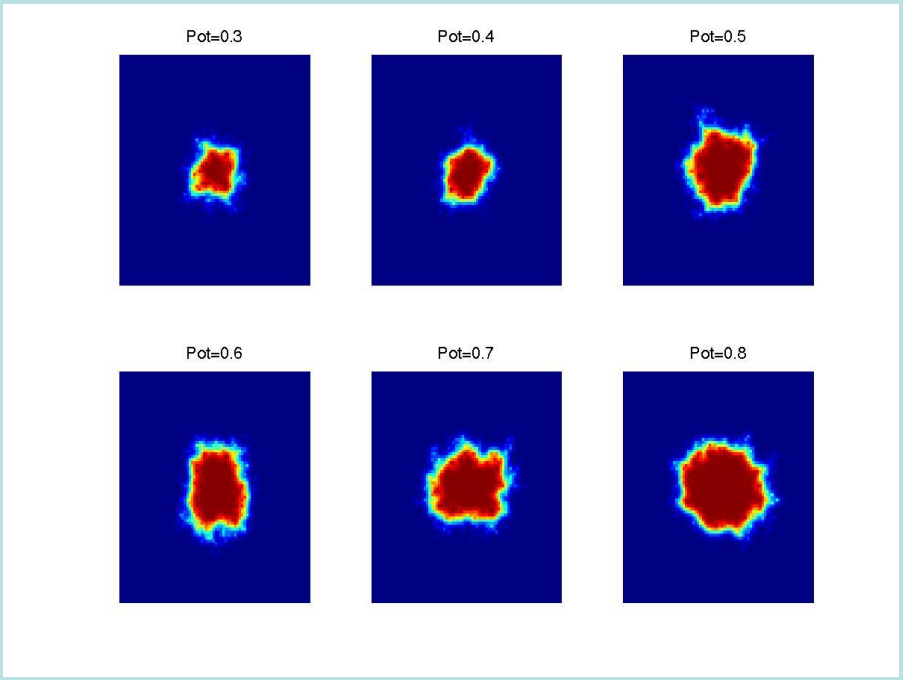
Comparison of Features



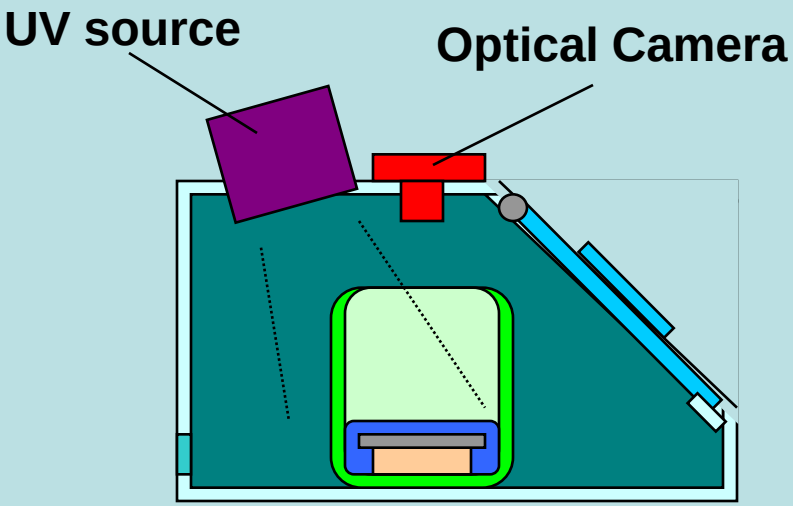


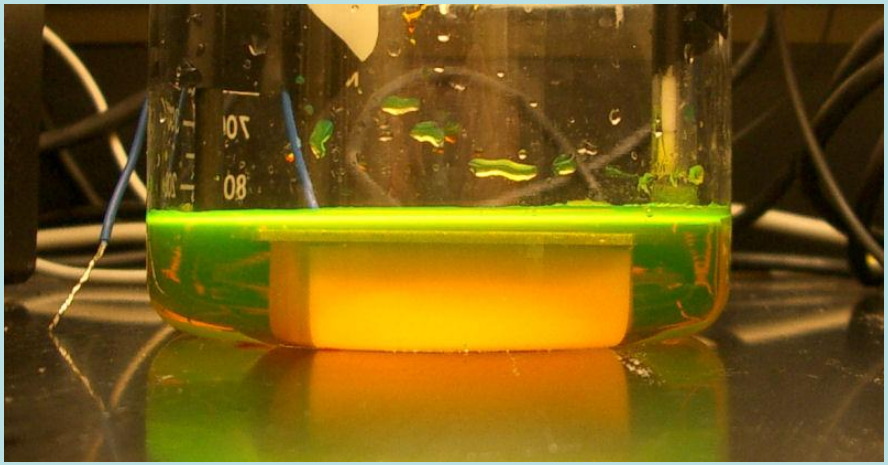
Effect of pH

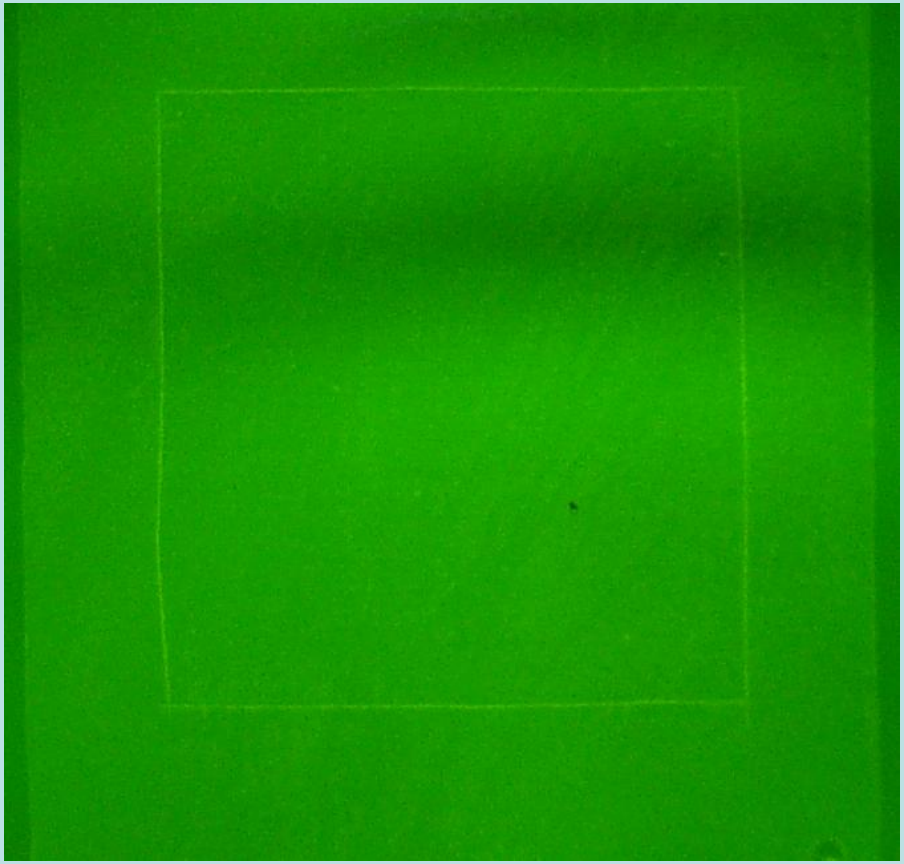
Effect of Potential



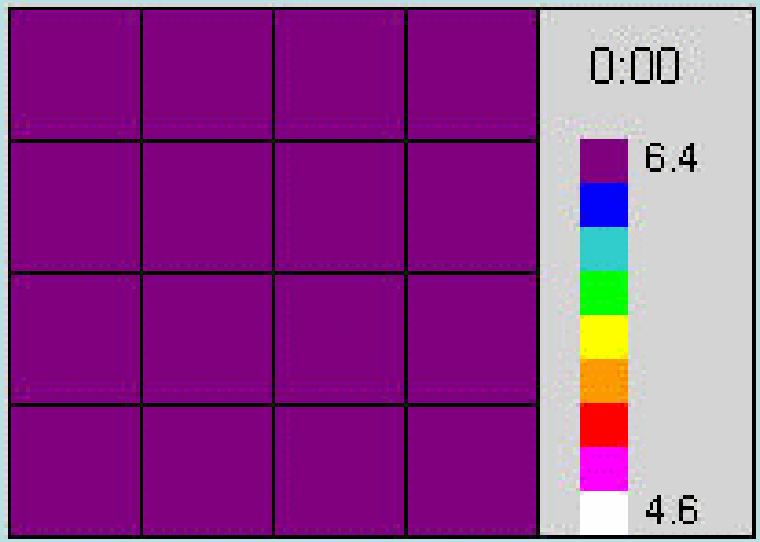
Corrosion Sensing through Fluorescence Imaging

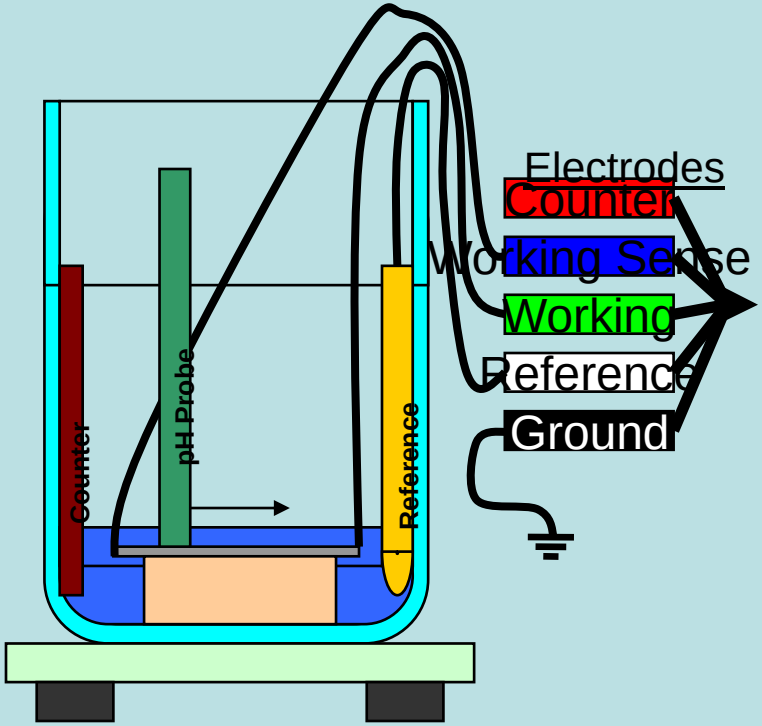


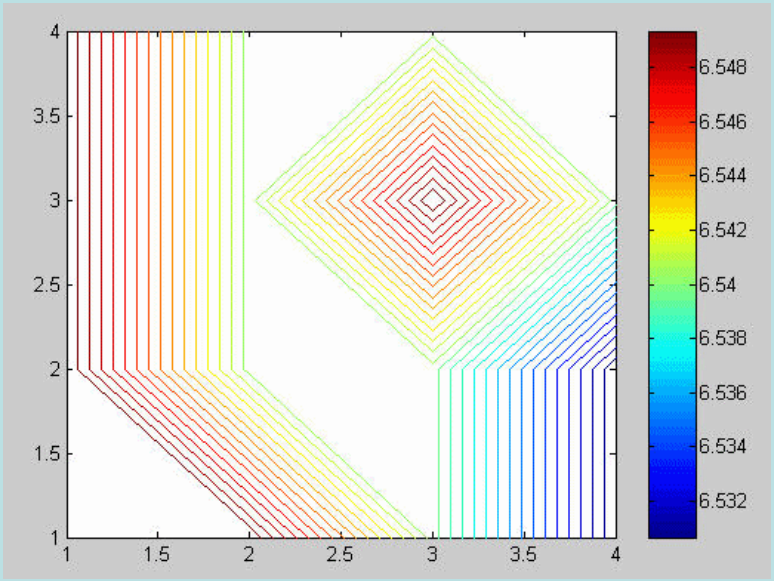




pH Mapping


0:00
6.4
4.6


Electrodes
Counter
Working Sense
Working
Reference
Ground
pH Probe
Counter
Reference


4
3.5
3
2.5
2
1.5
1
1
1.5
2
2.5
3
3.5
4
6.548
6.546
6.544
6.542
6.54
6.538
6.536
6.534
6.532

Pit Initiation/Growth – Governing Equations

Birth Probability

$$\lambda_1 = \lambda_0 \left[Cl^-\right] \exp\left(\frac{\alpha_\lambda F}{RT}\left(E - E_{crit}\right)\right)$$

λ_1 *is the birth probability*
λ_0 *is the intrinsic rate constant for birth of embryos*
Cl^- *is the Chloride concentration of solution*
α_λ *is constant*
F is faraday's constant
R is universal gas constant
T is the absolute temperature
E is the electrochemical potential applied to the surface
E_{crit} *is the critical potential over which pitting takes place*

Death Probability

$$\mu_1 = \mu_0 \left[OH^-\right] \exp\left(-\frac{\alpha_\mu F}{RT}\left(E - E_{pass}\right)\right)$$

μ_1 is the death probability of the embryo
μ_0 is the intrinsic constant for death of embryo
OH^- is the concentration of hydroxyl anion
α_μ is constant
E_{pass} is the potential under which the embryo repassivates
R is universal gas constant
T is the absolute temperature

Transition Rate

$$\gamma_1 = \gamma_0 \exp\left(-\frac{A_\gamma}{RT}\right)$$

γ_1 is the transition rate from embryo to stable pit
γ_0 is the intrinsic rate constant
A_γ is the apparent activation energy
R is universal gas constant
T is the absolute temperature

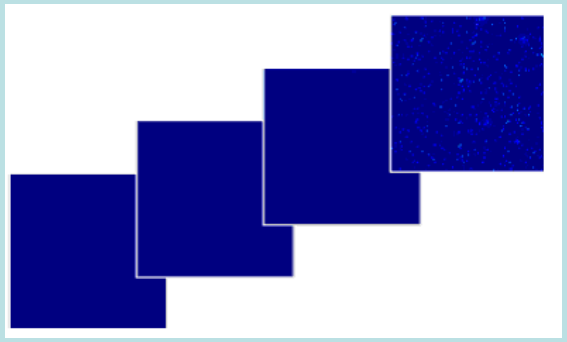
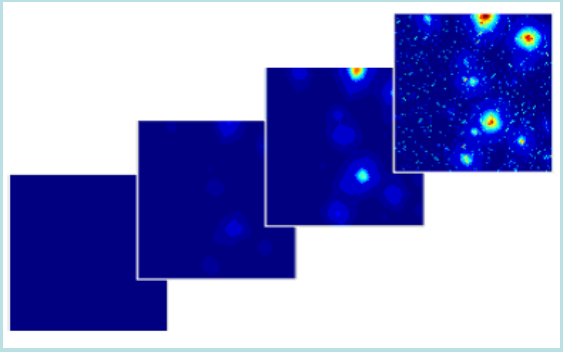
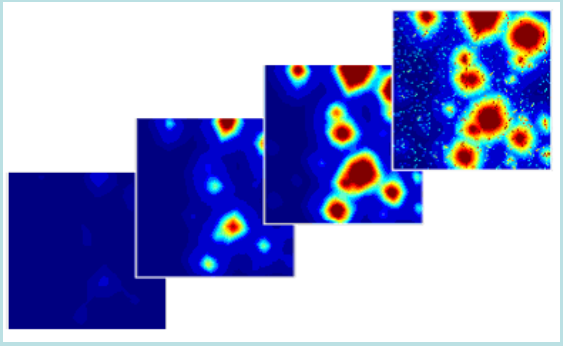
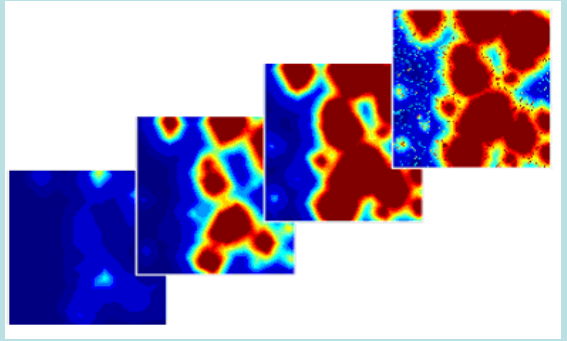
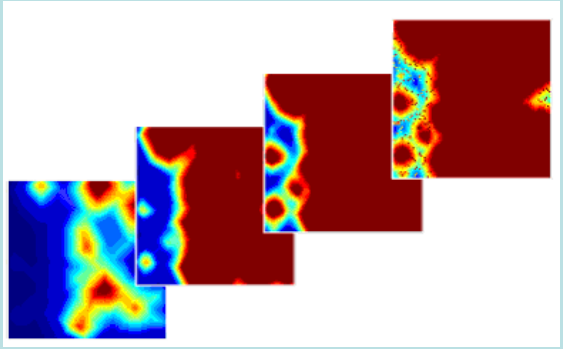
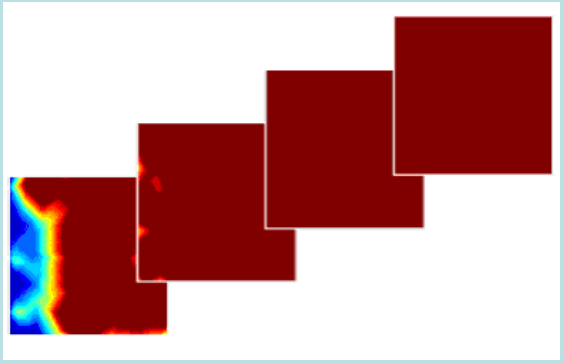
Pit Growth

$$\ln\left(\frac{\Delta r}{\Delta t}\right) = 13.409 - \left(\frac{5558.7}{T + 273}\right) - 0.087(pH) + 0.56965(Conc)$$

Δr/ Δt is the corrosion growth rate
T is the absolute temperature
pH is the pH of solution
Conc is the Concentration of solution

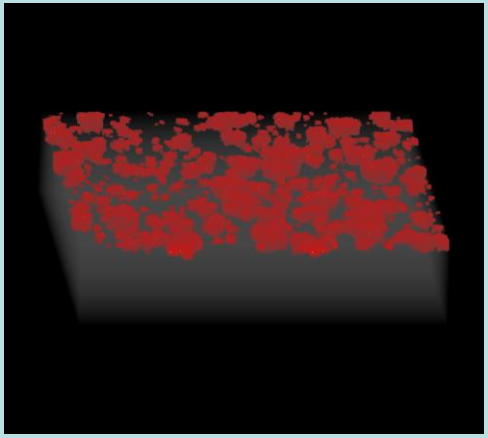
Farmer et al. (1998)

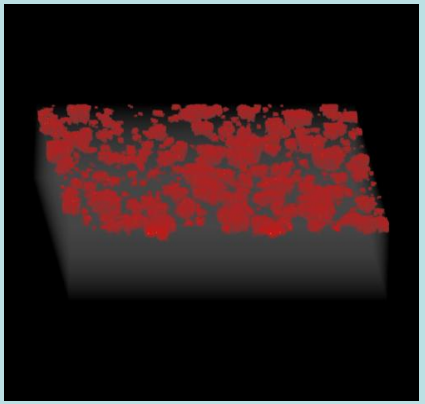
3-D Corrosion Simulation

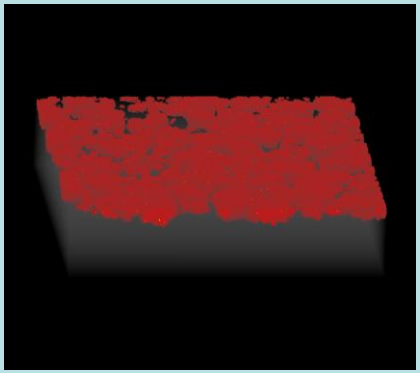







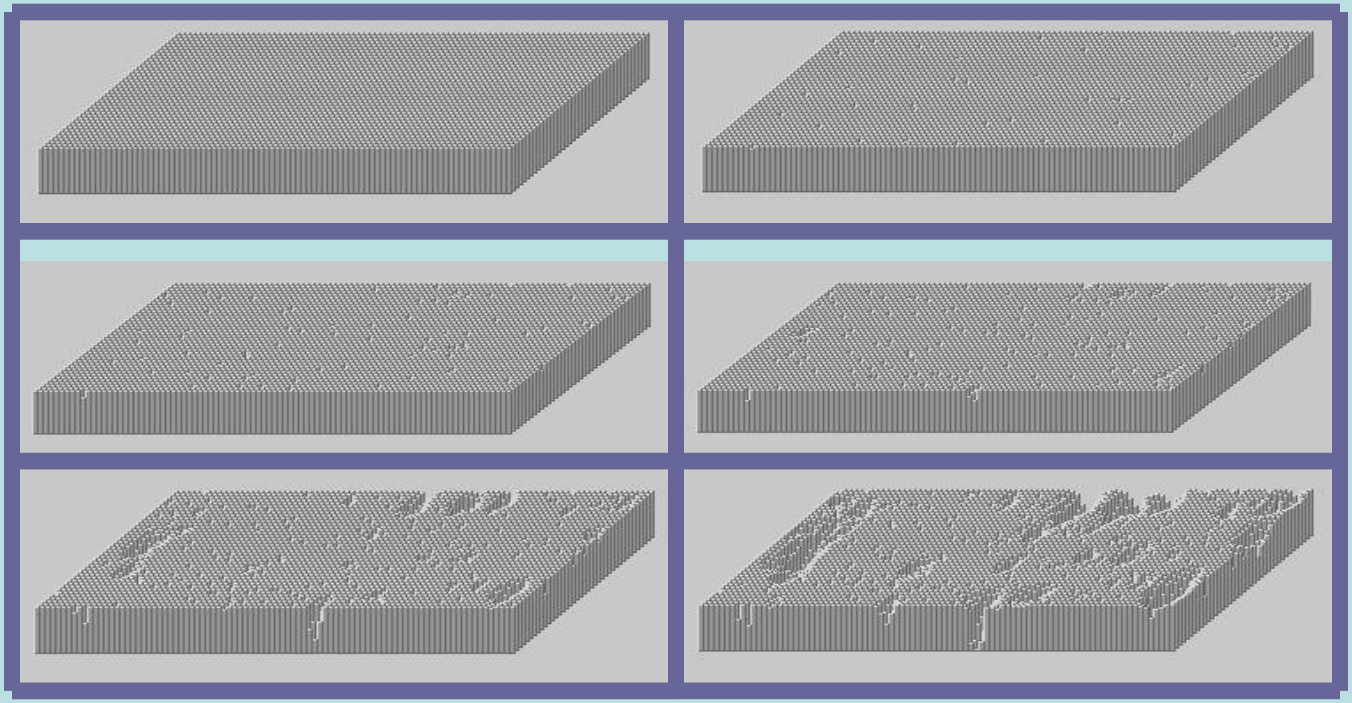
3D Visualization

- Computer program has been developed to simulate the 3D corrosion model.





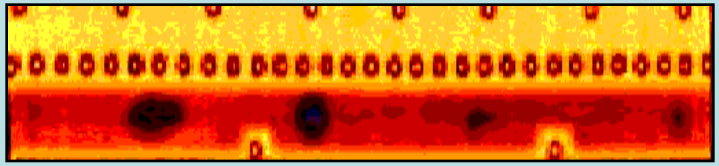




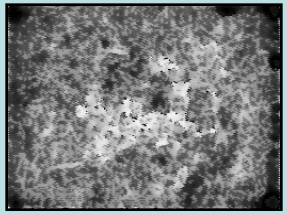
Corrosion Damage Assessment (Part II)

The Assessment Problem

Identify and Quantify corrosion on an NDI image

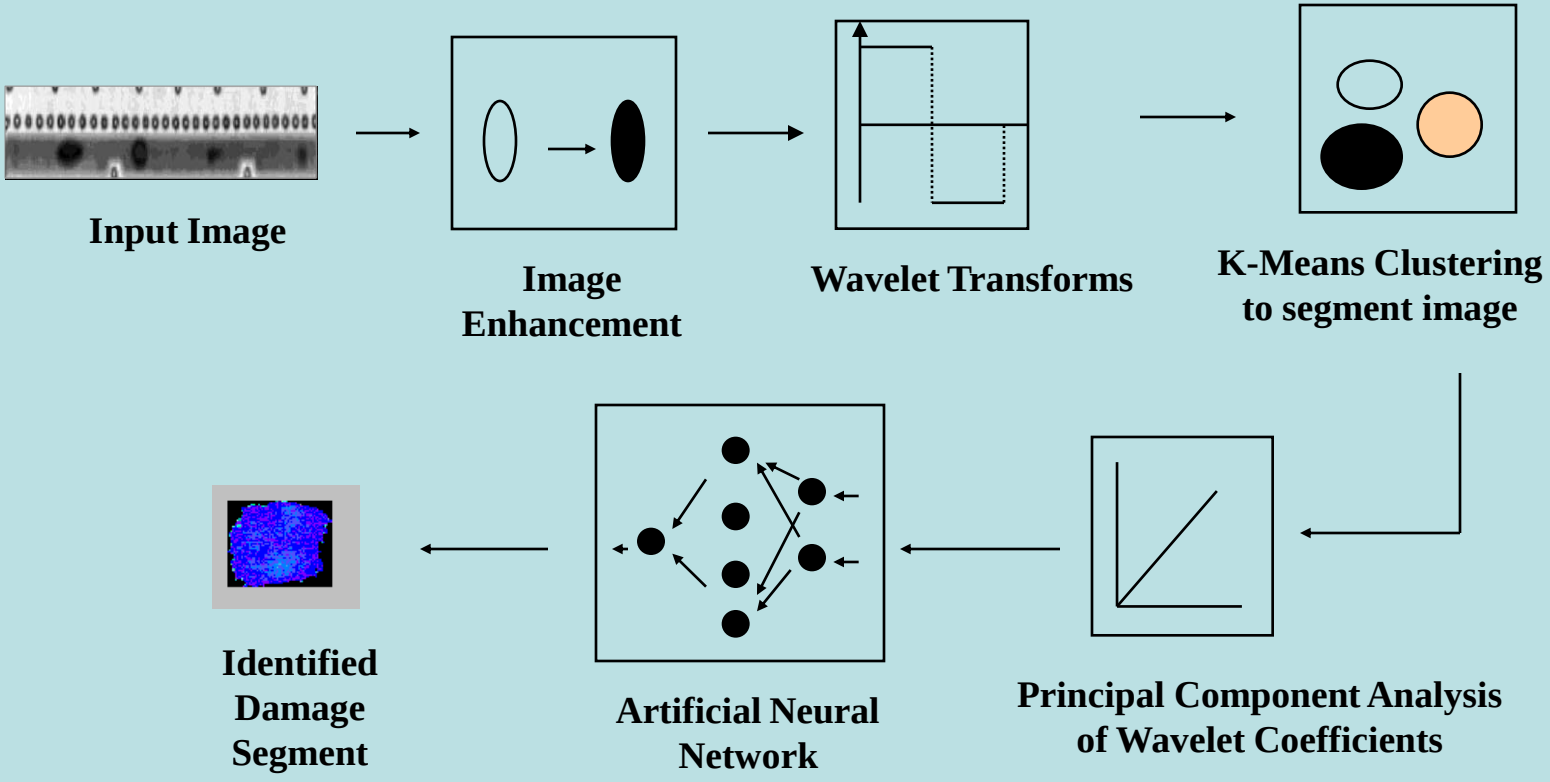


A panel with corroded regions

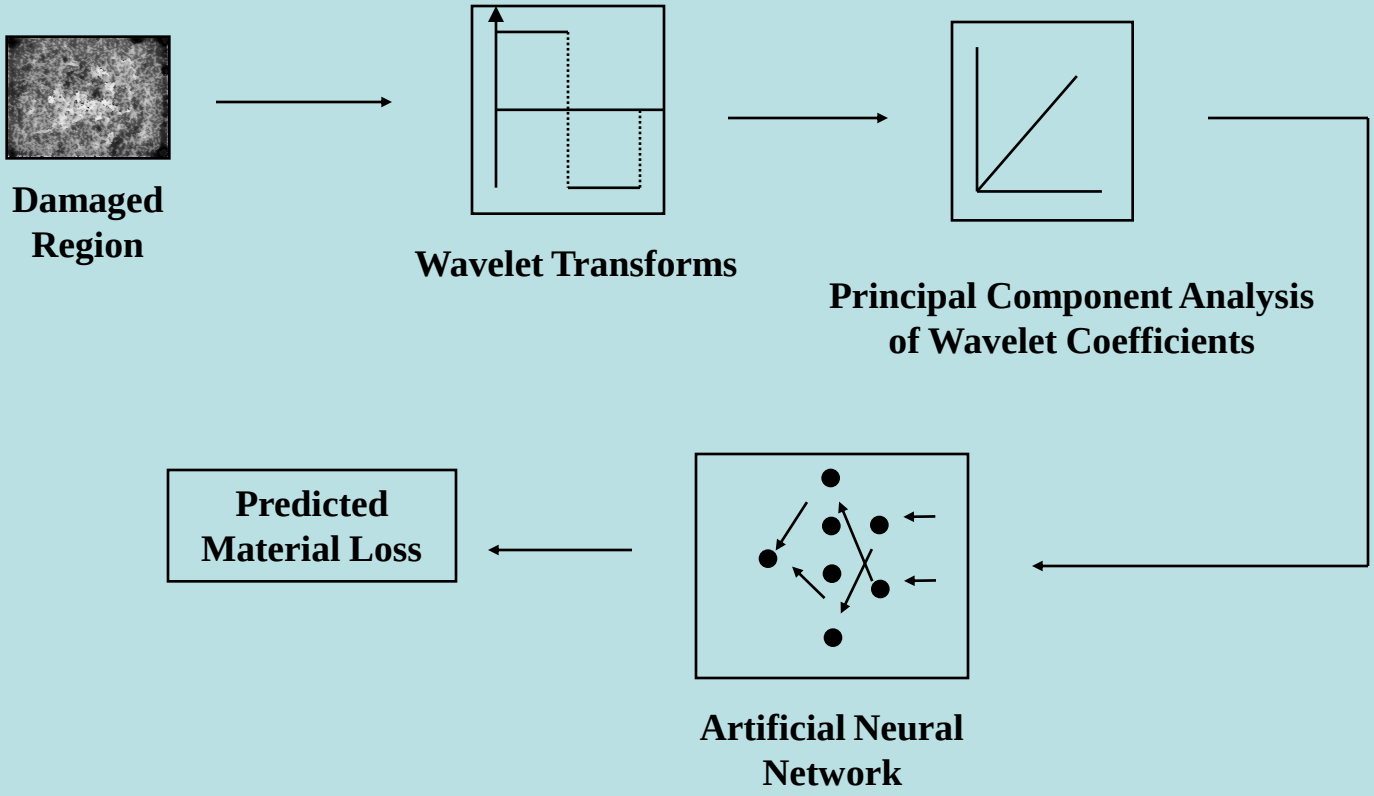


A corroded region

Identification Process

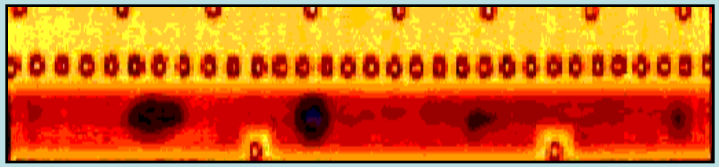


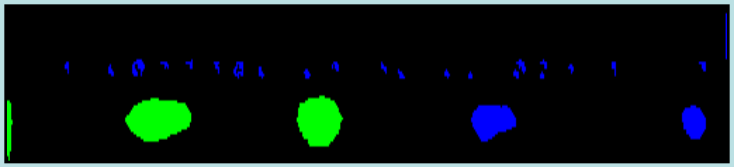
Quantification Process



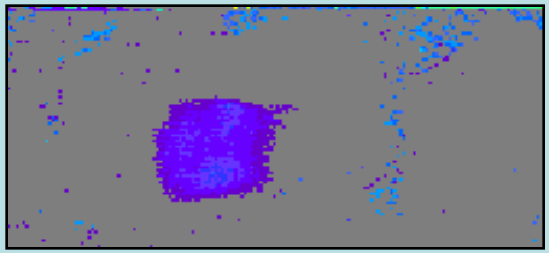
Identification/Quantification Results (FAA Data)

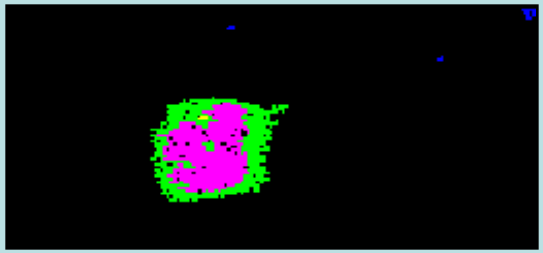
Eddy Current 5 kHz





Ultrasound 0.0425” pulse





Color Index

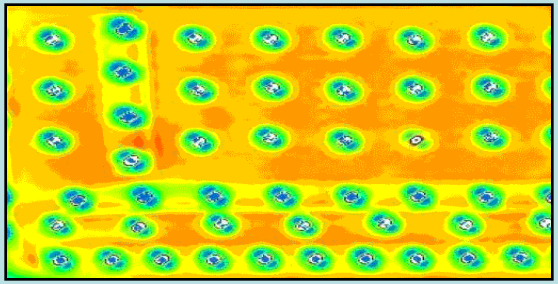
Blue 0-5% material loss Green 5-10% material loss

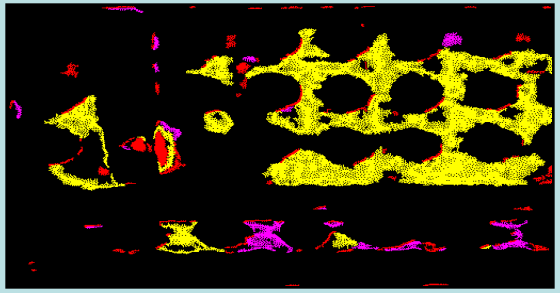
Yellow 10-15% material loss Magenta 15-20% material loss

Red 20-25% material loss

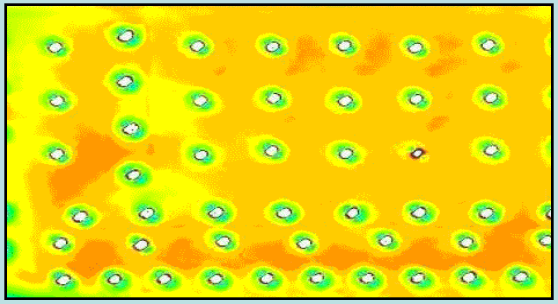
Identification/Quantification Results (US Air Force Data)

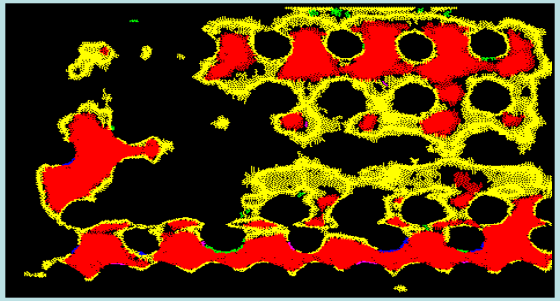
EC 2 kHz





EC 12 kHz





Color Index

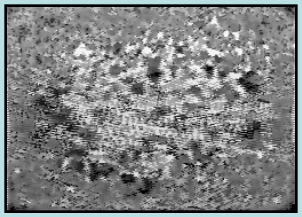
Blue 0-5% material loss Green 5-10% material loss

Yellow 10-15% material loss Magenta 15-20% material loss

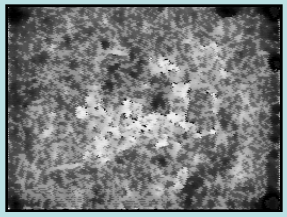
Red 20-25% material loss

Quantification Results (Raytheon Data)

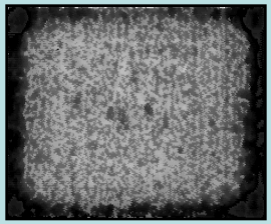
- Ultrasonic Images of Corrosion pits with varying material loss were used



10% loss

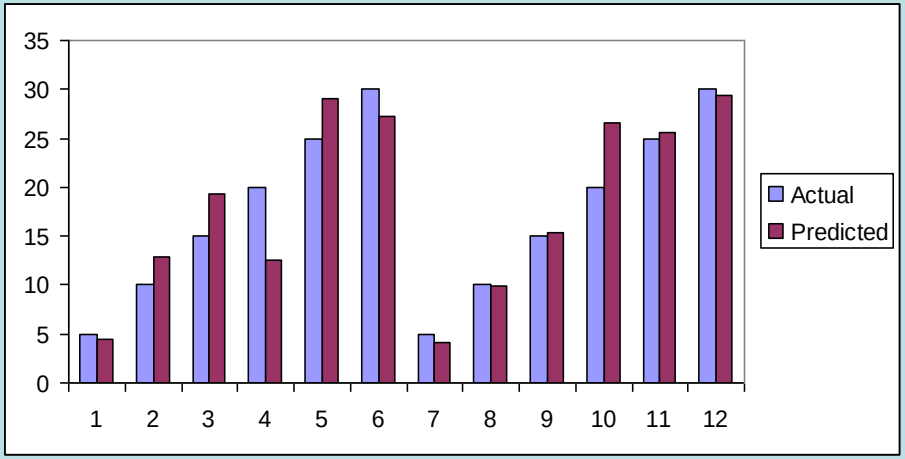


20% loss



30% loss

  - 72 for training
  - 12 for testing
- Error 15%



Severity Analysis

(Estimate the severity in terms of residual strength, material loss, and fatigue life)

***Damage* Prediction by Neural Networks**

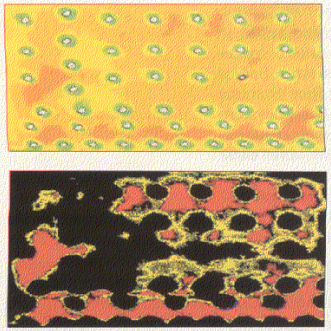
***Redesign* by Inverse Mapping of Neural Networks**

***Optimization by* Particle Swarm Method**

(Intelligent System)

Intelligent systems

Draper Laboratory continued development of its Earth Phenomena Observing System (EPOS), which integrates optimization and astrodynamic modeling to deliver an autonomous planning and execution system for collaborative groups of Earth observing satellites. As new stationary targets are identified, EPOS provides optimized sensor coverage of the target through in-plane phasing maneuvers and scheduled coasting plans using multiple heterogeneous satellites.



The original corrosion damage panel was obtained using nondestructive inspection based on eddy current at 12 kHz (top). Identified and quantified corroded regions were obtained from intelligent computations. The color index shows the material loss as, black, 0; blue, 0-5%; green, 5-10%; yellow, 10-15%; magenta, 15-20%; and red, 20-25%.

The Air Force Research Laboratory continued development of an on-board cluster management system for the TechSat 21 program. It comprises a distributed shared information system based on SCL; a formation flying control system based on ObjectAgent; and a fault-management system based on SCL and LivingStone. A joint venture with JPL will incorporate an autonomous planning system based on CASPER (Continuous Activity Scheduling Planning Execution and Replanning) and on-board science processing algorithms for optimization of science return.

Rice University researchers produced successful preliminary results in the development of a health and safety-of-flight decision tool using a regularization network variant, the Support Vector Machine (SVM). This tool will give engineers empirical guidance in edge-of-operational-envelope testing.

For example, dozens of system health and safety-of-flight parameters must be monitored during testing of Ames' one-quarter-scale full-span tilt-rotor aeroacoustic model of the V-22. Many time-dependent drivetrain temperatures operate near red-line limits and react differently to various test conditions. The SVM-based tool has accurately predicted the behavior of the temperatures as a function of 71 inputs in hover and forward-flight conditions.

A pattern recognition approach to recovering measured reflected solar and outgoing long-wave radiation from Earth has been implemented by a Clouds and Earth Radiant Energy System (CERES) instrument group at Scientific Applications International. When the instrument exhibited increased electronic noise and cross-talk between radiometric and diagnostic data, noise characteristics were captured by a feature-sensitive neural network. Removing noise and cross-talk from a daytime portion of the measured radiation spectrum enabled recovery of almost four weeks of radiometric data used for important cross-validation with two other CERES instruments operating on the Terra satellite.

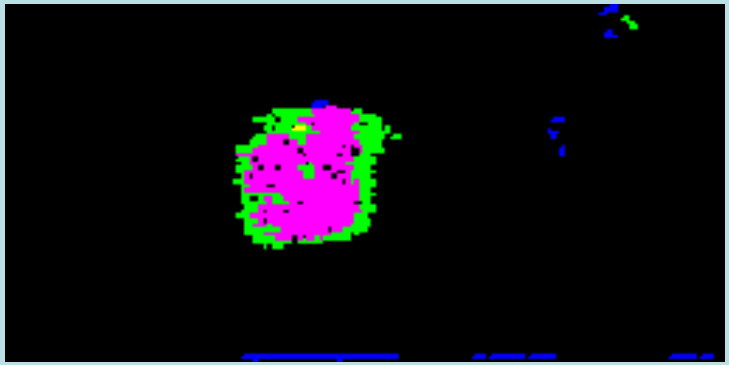
Charles River Analytics made progress in applying intelligent agents to air traffic control and uninhabited air/ground vehicle (UAV/UGV) domains. Intelligent agent models of air traffic controllers, dispatchers, and pilots were developed to study future Free Flight concepts. Intelligent agents were also developed for autonomous UAV operations, focusing on optimized search path generation for time-critical targeting, and inter-UAV coordination for enhanced flight autonomy. A terrain reasoning and path planning UGV agent, ROVANE, is being developed to aid scientists commanding the Mars Rover.

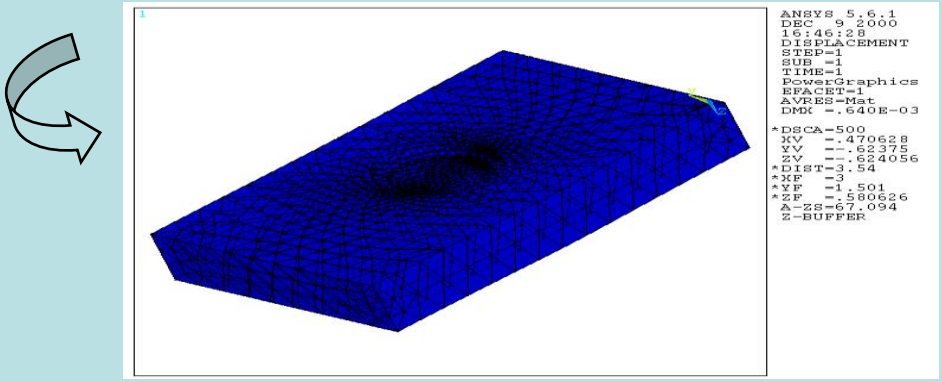
NASA-Johnson is developing Robonaut to function as an EVA astronaut equivalent. It jumps generations ahead by eliminating the robotic scars (such as special grapples and targets) and specialized robotic tools of traditional on-orbit robotics. However, it keeps the human operator in the control loop via its telepresence control system. Autonomy milestones archived include voice recognition/synthesis; human tracking; reading and writing tool information; to/from memory; and seeing a dangling wrench, reporting its pose, then autonomously positioning the right palm in alignment with the tool's handle for a grasp. These skills are now coming together for the milestone of delivering a tool to a human on voice command only.

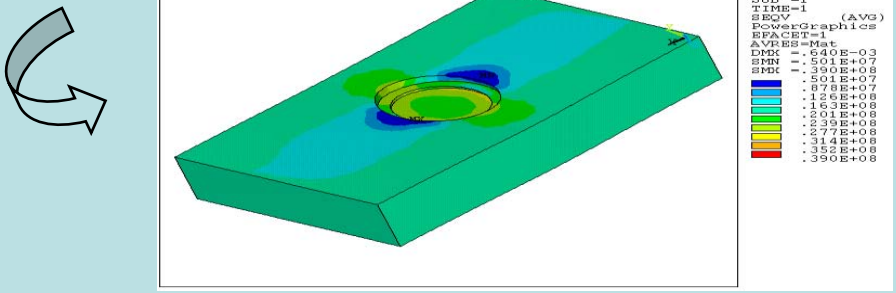
Purdue researchers are developing intelligent computations based on wavelets and neural networks to quantify the extent of corrosion damage in aircraft. The corrosion damage image obtained from a nondestructive inspection device can be submitted via the Internet, and the extent of the damage quantified and predicted. They are also developing methods, through neural network inverse mapping and evolutionary optimization techniques, for redesigning and predicting the structural durability of aging aircraft panels/materials. A

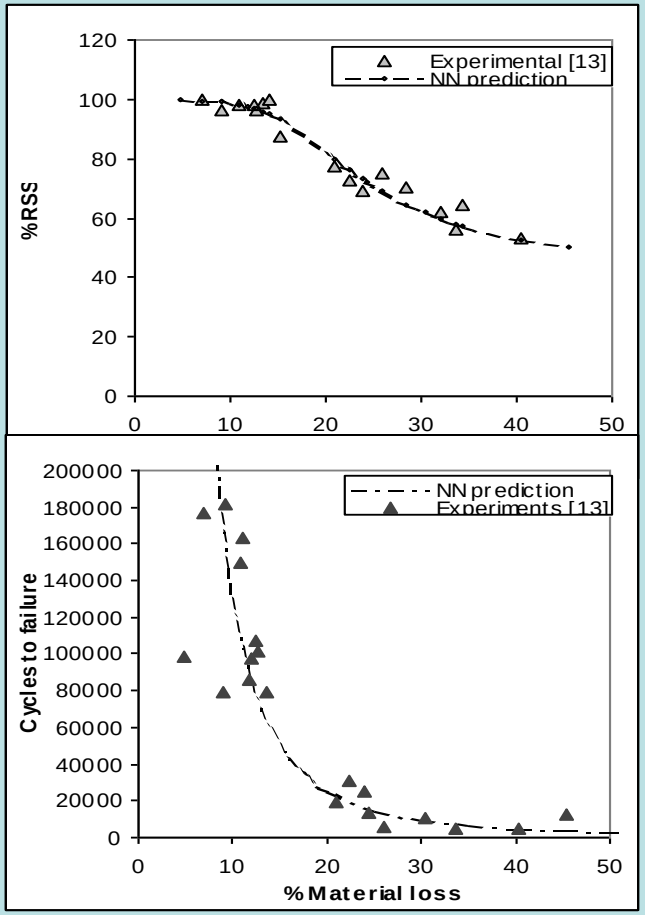
by **Paul Zetocha**

Correlation of Material Loss with Stresses, Strength, and Fatigue Life





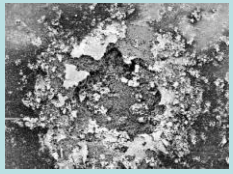




Corrosion Modeling / Simulation / Life Prediction - Overview

Computational Intelligence Methods

Corrosion

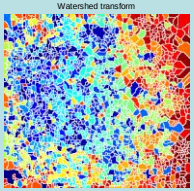


Identification

Modeling & Simulation

Neural Networks & CA PSO

Image Processing/ Wavelet Features



Material Loss

Corrosion Fatigue

Structural Integrity & Life Prediction

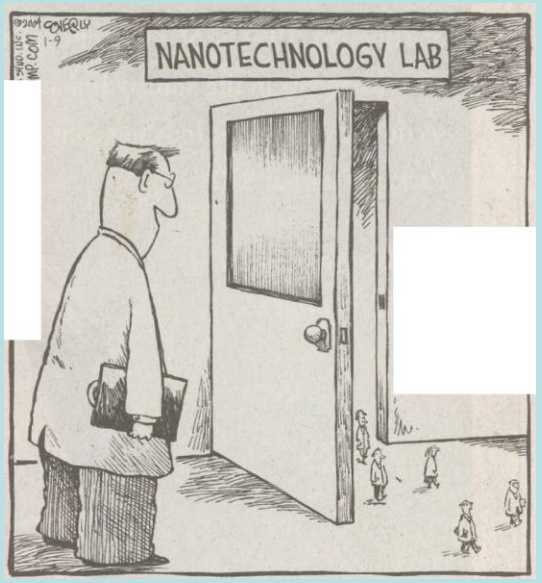
Summary

- Pitting Corrosion Modeling and Simulation
- Validation Studies with Experimental Data
- Corrosion Damage Assessment

Future Work

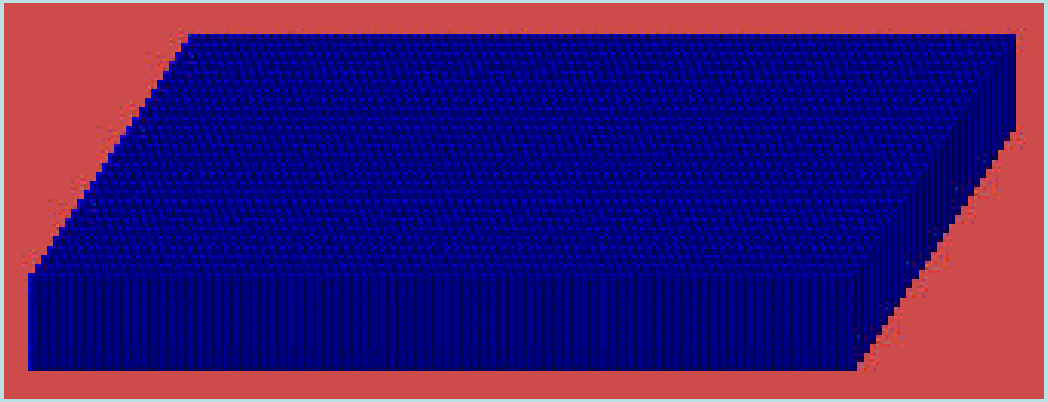
- Continue Modeling & Simulation to Predict Fatigue life and Structural Integrity due to Corrosion

- Multi-Scale (Nano-Micro-Macro-levels) Modeling of Corrosion Damage



Thanks !

Any Questions ?



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